Comparative Economic and Technical Analysis of Power Plants with CO$_2$ Capture

Presentation at the Aspen Global Change Institute Workshop on Industrial Carbon Management
July 22-28, 2000
Aspen, Colorado
by
Dale Simbeck
Vice President Technology
SFA Pacific, Inc.

Presentation Overview

Background
• SFA Pacific and our CO$_2$ mitigation work
• The electric utility industry is changing
• Why electric power generation will be forced to meet a disproportional share of any CO$_2$ reductions

Comparative economic and technical analysis of power plants with CO$_2$ capture or reduction
• Existing coal-fired power plant retrofits
• Cogeneration & polygeneration
• Status of worldwide gasification as this technology is key to both power plant CO$_2$ capture & polygeneration

Conclusions
SFA Pacific Background

Basis of name: founded in 1980 as Synthetic Fuels Associates & does extensive work in the Pacific Basin

Perform technical, economic & market assessments for the private industrial sector

Principal work in residual oil upgrading & electric power generation

Niche is objective outside opinion and comparative analysis before companies make major investments

No vested interest in technologies, R&D or project development

Representative SFA Pacific Clients

**UTILITIES**
- British Gas
- CEA (Canada)
- EdF
- Electrabel
- EPDC (Japan)
- EPRI
- Eskom
- GRI
- National Power
- Power Gen
- RWE/Rheinbraun
- Tokyo Electric Power
- Tokyo Gas
- TransAlta
- Vattenfall

**INDUSTRIALS**
- BP/Amoco/ARCO
- BHP
- Chevron
- Chinese Petroleum
- Dow/Destec
- DuPont/Conoco
- ENI
- Exxon/Mobil Oil
- PDVSA
- Saudi Aramco
- Shell International
- Statoil
- Texaco
- TOTAL/Fina/Elf
- Veba

**VENDORS, E&C**
- ABB
- Babcock & Wilcox
- Black & Veatch
- Bechtel
- Cummins
- Fluor Daniel
- Foster Wheeler
- GE
- IFP
- Kellogg/ Brown & Root
- Kvaener
- Lurgi
- MHI
- Siemens/Westinghouse
- Weyerhaeuser
SFA Pacific Background in GHG Issues

World Bank - Efficiency & environmental impact of coal use in China

United Nations - Several energy & environmental projects/conferences

China - International consultant to the People’s Republic of China
National Response Strategy for Global Climate Change

Global Environmental Facility (GEF) - Recommendations &
suggestions on coal technologies in a carbon constrained world

U.S. DOE

- Review of policy & energy technology sections of 1995 IPCC draft
- Objective analysis of CO\textsubscript{2} control options for electric power
generation (see our 3 papers for the GHGT-4 & GHGT-5 conferences)

Several major private client analyses

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Kyoto Protocol Has Several Fatal Flaws

Ignores developing nations - most of the world’s CO\textsubscript{2} growth

- Requires simple, fair & transparent Joint Implementation, Clean
Development Mechanism & CO\textsubscript{2} emission trading. However, vested
interests want subsidies, not simple, fair & transparent systems

Most CO\textsubscript{2} reduction burden on U.S. - 26% reduction from 2000

- Highly unlikely that the U.S. will ratify - “It’s the economy, stupid”
- See the October 1998 EIA Kyoto Report to Congress - SR/OIAF/98-03

“Leakage” would likely increase CO\textsubscript{2} growth by economically
forcing CO\textsubscript{2} intensive industries in Annex I nations to move
production to cheaper but less efficient & coal-based
developing nations like China

- Globalization & free trade forces companies to be cost competitive
- Governments cannot force companies to stay & be non-competitive
Fundamental Changes in Power Generation

Deregulation, increased competition & globalization

- Restructuring: takeovers, asset resales & upgrades to create large, more economically efficient Genco, Transco & Disco systems
- Convergence of power, gas & oil industries into large more cost & fuel efficient power generators (Genco)
- ISO or RTO of transmission (Transco) to assure system reliability
- Time of day rates (both buying & selling) & distributed generation to improve distribution (Disco) as well as overall system utilization

Uncertainties in all areas of power generation

- Applications, markets, technology & prices
- Feedstocks: options, availability & price
- Environmental requirements have an increasing impact with CO₂ reduction & sequestration being the greatest long term challenge

World Energy, GDP & Population Trends

Clearly Show Electricity is the Energy of the Future

Power Generation Will Be Forced to Meet a Disproportionate Share of Any CO₂ Reductions

Environmental hypocrites driving urban assault vehicles (SUVs) have more votes than CO₂ intensive industries

Power plants can not move to China, as many CO₂ intensive industries in Annex I nations will, if faced with carbon taxes

Large potential for cost & efficiency improvements in power generation thanks to deregulation
  • However, this only reduces the rate of CO₂ growth, few reductions

Ultimately must face up to CO₂ reduction & CO₂ sequestration
  • Largest point sources of CO₂ are coal-fired power plants
  • Replace coal with NG, renewables & waste fuels where economical
  • However, fossil fuels with CO₂ sequestration will likely be required

CO₂ Retrofit of Existing Coal Power Plants

Background
  • Existing pulverized coal (PC) boiler power plants generate over 45% of the total annual power in North America (over 55% in the U.S.)
  • They have the highest CO₂ emissions yet the lowest power costs
  • Low cost due to paid-off facilities, low operating cost & emissions “grandfathering” (not required to meet same emissions as new units)

Advantages to CO₂ retrofit of existing PC power plants
  • Location, location, location
  • Existing power & fuel transportation & handling infrastructures
  • Ease of permitting as any major retrofit greatly reduces all emissions
  • Potential to greatly up-rate capacity at these existing sites
TransAlta

An innovative & forward thinking company that began as an investor-owned regulated electric utility in Western Canada

Now an international power generator

- Numerous NGCC cogeneration IPPs in Canada & New Zealand
- Industrial cogeneration at the large Tar Sands upgrader facilities
- Large existing PC power plants in Canada & the United States

One of the few electric power generators that is objectively addressing & economically analyzing the GHG issue

- See GHG section of the TransAlta web site at www.transalta.com
- Funded two analyses of CO\textsubscript{2} recovery for existing PC power plants
  - Flue gas amine scrubber by Fluor Daniel
  - O\textsubscript{2} combustion with flue gas recycle by ABB (CE & Lummus)

Comparative Analysis of CO\textsubscript{2} Capture

SFA Pacific had already developed a simple & transparent analysis to compare CO\textsubscript{2} options for new power plants

- See 1998 GHGT-4 paper
- Based on single page spreadsheet for each option showing:
  - Principal energy & material balance in just MW\textsubscript{e}, MW\textsubscript{th} & mt/h
  - Capital cost build-up for all key processes via consistent unit costs
  - Costs of electricity & CO\textsubscript{2} avoidance via consistent economic inputs
  - Baseline is power cost & CO\textsubscript{2} emissions of a new state-or-the-art NGCC

TransAlta analysis presented an opportunity to modify the SFA Pacific analysis for existing power plant CO\textsubscript{2} options

- Table 1 in GHGT-5 retrofit paper is an example of the single page spreadsheet modified for an existing coal power plant CO\textsubscript{2} retrofit
Existing Coal Power Plant CO₂ Retrofit Options

Conversion to lower carbon fuels without CO₂ recovery

- Natural gas - new NGCC & NG-GT repowering
- Biomass/coal co-firing - 10% of PC feed & 50% via biomass gasifier
- More efficient coal use via CGCC-coal gasification combined cycle

Conversion with CO₂ recovery technologies

- PC retrofits for TransAlta work: flue gas scrubber & O₂ combustion
- H₂-fired CC via NG & coal gasification - CO₂ scrubbed from HP H₂
- Included H₂-CGCC & PC flue gas scrubber for 65% CO₂ reduction so same CO₂ emissions as a new NGCC without CO₂ recovery

Conversion to no net CO₂ emissions technologies

- Biomass GCC, nuclear & wind turbines

Basis for Comparing CO₂ Retrofit Options

Complexities of comparing existing power plant CO₂ retrofits

- Baseline power cost & emissions - old PC or new NGCC - as this has a major impact on both the power & CO₂ emissions avoidance costs
- Handling of old existing PC investment that is not yet fully amortized (paid-off) versus the new retrofit investment
- Handling loss of efficiency & capacity due to CO₂ recovery retrofit

Basis chosen to assure the most objective comparison

- Used existing PC power plant as baseline for costs & emissions; thereby low power costs but at high CO₂ emissions per MWh
- Refinanced any remaining old capital with the new retrofit capital
- CO₂ & O₂ production included in power plant costs & internal power + new NGCC capacity as required to maintain original net capacity
- No renewable subsidies or credits for other PC emission reductions
Coal Power Plant CO$_2$ Retrofit Results

See Table 2 of GHGT-5 retrofit paper for summary of results

Continued coal use with CO$_2$ recovery retrofit is favored if the high pressure CO$_2$ obtains a slight byproduct credit

- Current & future potential uses include enhanced oil recovery (EOR) & coal bed methane (CBM) recovery

If the CO$_2$ is a disposal cost, replacement with a new NGCC without CO$_2$ recovery is favored over coal with CO$_2$ recovery until NG prices reach about $6 per million Btu

Co-firing NG or biomass with coal has low costs but only moderate CO$_2$ reductions

- Favors NG-GT repowering due to efficiency & capacity gain while maintaining the coal option for the future via CGCC or H$_2$-CGCC

Proposed CO$_2$ Sequestration Projects That Reduce Costs Via Slight Byproduct Value

- Dakota Gasification - CO$_2$ recovery from existing coal gasification SNG for enhanced oil recovery (EOR) in Canada
- Shell Oil Pernis Refinery - CO$_2$ recovery from existing residual oil gasification polygeneration for use in greenhouses
- China - CO$_2$ recovery from existing coal gasification ammonia for deep un-mineable coal bed methane (CBM) recovery
- Alberta, Canada - CO$_2$ recovery from existing coal power plant for improved tar sands EOR
- BP/Amoco & ARCO Alaska North Slope - CO$_2$ recovery from existing gas turbines or others sources for improved EOR
Coal Power Plant CO₂ Retrofit Results

Of the CO₂ recovery options H₂-CGCC has advantages over both PC retrofit flue gas scrubber or O₂ combustion

- PC retrofits reduce both capacity & efficiency by about a third where as new H₂-CGCC @ same $/kW increases both capacity & efficiency
- O₂ combustion requires 4.5 times more O₂ per net MW coal capacity

The 65% CO₂ recovery option with coal (same as new NGCC) helped the PC retrofit flue gas scrubber option the most.

The renewables & nuclear options have limitations

- Nuclear: high costs, decommissioning, waste & liability issues
- Wind turbines: low annual load factor & required backup generation
- Biomass: high costs, supply & land limitations & transportation cost
  - At only $500/ha/yr gross costs / 5 mt carbon/ha/yr = $100/mt carbon in-field plus transportation & utilization costs + 340 hectares per MW

Coal Power Plant CO₂ Retrofit Conclusions

CO₂ capture for existing coal-fired power plants must be included in any objective analysis of CO₂ mitigation options

- Key issue: can high pressure CO₂ find a small byproduct value
- CO₂ byproduct markets already exist & are growing for EOR & CBM
- Should favor this option in areas of coal power plants, EOR & CBM

Large potential for CO₂ capture technology improvements

- This analysis only included commercial technologies
- Best opportunities appear to be gasification, CO₂ scrubbers (both LP flue gas & HP syngas), air separation, gas turbines & fuel cells
- Also good opportunities for improvements in technology integration

The single page spreadsheet analysis facilitates objective identification & comparison of various CO₂ options
Cogeneration & Polygeneration

Background

- The SFA Pacific single page spreadsheet comparative technical & economic analysis of CO₂ mitigation options began with a focus on traditional central power plants
- This makes the analysis & comparisons easy to understand

However, the ongoing deregulation of electric utilities is fundamentally changing the future of power generation

- Allows non-utility generators to sell power to the grid at a fair price
- This gives cogeneration key advantages over central power plants
- Sales of cogen power to the grid also favors the use of gas turbines
- Strong growth of cogeneration in nations that have deregulated

Large Cogeneration Potential

The European cogen experience clearly shows there is significantly more cogen potential than many believed

- The Netherlands is delaying large cogen projects due to excess power
- New cogen application like gas turbine exhaust for crude oil heaters

There is still large potential for additional cogen in North America once full deregulation & baseload power is needed

- Expect “PURPA-2” type cogen incentives or efficiency tax credits

The Japanese Gas Association 1991 Industrial Repowering Analysis showed big potential (17,500 MWₜ), large power efficiency gain (16%), & major CO₂ reduction (50 MM t/yr)

Major cogen opportunities in China once power is deregulated

- 60% of China’s total coal use is not used in central power plants
Maximum Power in Total Cogeneration Clearly Favors Gas Turbines Over Steam Turbines

For a given heat host, 5 times more power with GT vs ST
This is the key issue as true cogeneration is heat host limited

Power-to-Steam ratio: kWe per t/hr cogen 10 bar steam (no steam to condenser)

Baseline for Cogeneration Analysis

See Table 1 of GHGT-5 update of new power plant paper

New “state-of-the-art” NGCC central power plant - 400 MW_e
New natural gas industrial boiler - 342 MW_th or 614 mt/h steam

- This size matches the NGCC heat recovery steam generator (HRSG)
- Medium pressure steam typical of industrial requirements

Estimated capital cost, efficiency & CO₂ emission

- For each (NGCC power & NG boiler steam) plus total of both

Estimated annual revenue requirements & product costs

- For each (NGCC power & NG boiler steam) plus total of both
- Identical price of natural gas & capital recovery factor
Cogeneration Results

See Table 1 of GHGT-5 update of new power plant paper

- Assumed identical power & steam rates to “keep it simple”
- Assumed the same economic inputs to keep it fair
- Conservative cogen design making MP (not LP) steam plus the extra capital cost to convert all this cogen steam into power for flexibility

Cogeneration reduced CO₂ emissions by 24% while at the same time reducing total capital & revenue requirements

- This creates a negative cost of CO₂ avoidance

Assuming steam value at only 75% of industrial boiler estimate still reduced the power costs from 3.6 to 3.1 cents per kWh

- 10 atm. MP steam value in cogen was only $6.90 per mt

Two Additional Cogeneration Options

Smaller cogeneration for commercial applications

- 1.0 MWₑ & 1.0 MWₜₜ of hot or cold water for space heating/cooling
- Based on NG-fired reciprocating engine (RE) with hot water heat recovery & bromine absorption refrigeration cooling
- High power-to-heat ratio & operating flexibility favor RE
- All commercially proven technology

Larger industrial polygeneration application

- 400 MWₑ + 400 MWₜₜ steam + 400 MWₜₜ methanol (1,732 mt/d)
- Based on coal gasification to generate clean synthesis gas for once-through slurry-phase MeOH followed by gas turbine cogen
- All commercially proven technology
Small Cogen & Large Polygeneration Results

Same positive results as the NGCC cogeneration

However, the baseline assumptions are more debatable

• Small cogen alternative baseline could be a lower unit cost NGCC based power for the grid plus an electric heat pump

• Large coal-based polygeneration alternative baseline could be NGCC & NG-based MeOH, thereby much lower CO₂/MWhₑ baseline

Nevertheless, both have efficiency advantages that are enhanced by CO₂ concerns & deregulation of power gen.

Gasification polygeneration is also synergistic with H₂, once-through liquid phase DME & F-T as well as CO₂ recovery

What is Polygeneration

Defined as gasification to make synthesis gas (H₂ & CO) for GT-based cogen steam/power + syngas chemicals & fuels

Shell Pernis refinery project is a good example, no subsidies

• Pitch gasification - 3 units (if all 3 to GCC power about 400 MWₑ)

• However, two gasifiers for refinery H₂ & third gasifier for GCC cogen with 2 GE 6B’s (115 MWₑ + refinery steam) with NG back-up

Great potential for polygeneration in the future due to ongoing deregulation of all energy sectors, but especially power gen.

• Use of low value “opportunity fuels” high in metals, nitrogen & sulfur

• Offers greater flexibility than traditional power plant relative to fuels, products, revenues, emissions, efficiency & annual capacity factors

• Even attractive for CO₂ recovery (will likely add this to Pernis)
Gasification

Gasification is simple & commercially well proven technology

Gasification is traditionally used for manufacture of synthesis gas (H₂ & CO) for chemicals such as ammonia fertilizer

New gasification applications are emerging due to:

• Growth & deregulation of electric power generation
• Improved gas turbines
• Stringent emissions mandates (air & solid wastes)

A database of “real” gasification projects is a powerful tool to assess the role of gasification in current & future markets

• Developed by SFA Pacific with financial support of U.S. DOE & technical support of the Gasification Technology Council members

Cumulative Worldwide Gasification Capacity in MWth Synthesis Gas Output

Source: SFA Pacific, Inc. for the U.S. Department of Energy

MWth syngas

Planned

Real

0 10,000 20,000 30,000 40,000 50,000 60,000 70,000

Gasification by Application
Large Growth in Power due to Deregulation

MW_{th} syngas

Source: SFA Pacific, Inc. for the U.S. Department of Energy

Gasification by Country

MW_{th} syngas

Source: SFA Pacific, Inc. for the U.S. Department of Energy
### Gasification by Primary Feedstock

<table>
<thead>
<tr>
<th>Feedstock/Products</th>
<th>MW_{th} syngas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>5,000-30,000</td>
</tr>
<tr>
<td>Petroleum</td>
<td>10,000</td>
</tr>
<tr>
<td>Gas</td>
<td>15,000</td>
</tr>
<tr>
<td>Petcoke</td>
<td>20,000</td>
</tr>
<tr>
<td>Biomass &amp; Wastes</td>
<td>25,000</td>
</tr>
</tbody>
</table>

Source: SFA Pacific, Inc. for the U.S. Department of Energy

### Top 10 Real Commercial Gasification Projects

<table>
<thead>
<tr>
<th>Plants</th>
<th>Location</th>
<th>Gasifiers</th>
<th>MW_{th} syngas</th>
<th>Year</th>
<th>Feedstock/Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sasol-II</td>
<td>S. Africa</td>
<td>Lurgi</td>
<td>4,130</td>
<td>1977</td>
<td>coal / F-T liquids</td>
</tr>
<tr>
<td>Sasol-III</td>
<td>S. Africa</td>
<td>Lurgi</td>
<td>4,130</td>
<td>1982</td>
<td>coal / F-T liquids</td>
</tr>
<tr>
<td>Repsol</td>
<td>Spain</td>
<td>Texaco</td>
<td>1,654</td>
<td>2004</td>
<td>residue / electric</td>
</tr>
<tr>
<td>Dakota</td>
<td>USA</td>
<td>Lurgi</td>
<td>1,545</td>
<td>1984</td>
<td>lignite / SNG</td>
</tr>
<tr>
<td>SARLUX</td>
<td>Italy</td>
<td>Texaco</td>
<td>1,067</td>
<td>2000</td>
<td>residue / electric</td>
</tr>
<tr>
<td>Shell MDS</td>
<td>Malaysia</td>
<td>Shell</td>
<td>1,032</td>
<td>1993</td>
<td>NG / F-T liquids</td>
</tr>
<tr>
<td>Linde</td>
<td>Germany</td>
<td>Shell</td>
<td>984</td>
<td>1997</td>
<td>residue / H_2&amp;MeOH</td>
</tr>
<tr>
<td>ISAB</td>
<td>Italy</td>
<td>Texaco</td>
<td>982</td>
<td>1999</td>
<td>residue / electric</td>
</tr>
<tr>
<td>Sasol-I</td>
<td>S. Africa</td>
<td>Lurgi</td>
<td>911</td>
<td>1955</td>
<td>coal / F-T liquids</td>
</tr>
<tr>
<td>Total/EdF/</td>
<td>France</td>
<td>Texaco</td>
<td>895</td>
<td>2003</td>
<td>residue / electric</td>
</tr>
</tbody>
</table>

Source: SFA Pacific, Inc.
### Gasification Projects without Subsidies

<table>
<thead>
<tr>
<th>Chemicals from coal or pet coke</th>
<th>MW&lt;sub&gt;th&lt;/sub&gt; syngas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ube Ammonia - Japan</td>
<td>295</td>
</tr>
<tr>
<td>Farmland - Kansas, USA</td>
<td>295</td>
</tr>
<tr>
<td>Eastman Chemicals - Tennessee, USA</td>
<td>190</td>
</tr>
</tbody>
</table>

**Refinery polygeneration from pitch or coke**

<table>
<thead>
<tr>
<th>Company</th>
<th>MW&lt;sub&gt;th&lt;/sub&gt; syngas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repsol - Spain</td>
<td>1,545</td>
</tr>
<tr>
<td>Total/EdF/Texaco - France</td>
<td>895</td>
</tr>
<tr>
<td>Exxon - Texas, USA &amp; Singapore</td>
<td>800</td>
</tr>
<tr>
<td>Shell - the Netherlands</td>
<td>637</td>
</tr>
<tr>
<td>Nippon Oil - Japan</td>
<td>620</td>
</tr>
<tr>
<td>Motiva - Delaware, USA</td>
<td>588</td>
</tr>
</tbody>
</table>

### Driving Forces for Gasification

The facts clearly show that gasification is alive & well

- Annual growth of about 3,000 MW<sub>th</sub> syngas or 7% of total capacity

**Fuel of choice for new projects are “opportunity fuels”**

- Usually higher in sulfur & heavy metals than coal
- Many have lower capital & feedstock costs than coal

**Current surge in gasification projects is in electric power applications in countries with electric power deregulation**

- Gasification enables gas turbine based cogeneration at much higher power-to-cogen heat ratio than possible with steam systems
- Polygeneration offers technical, economic, environmental & efficiency advantages that are impossible in a central power plant
Conclusions

Electric power generation will be forced to meet a disproportionate share of any CO\textsubscript{2} reductions

- Both new & existing power generation facilities must be addressed

Large potential for lower costs & higher efficiency in new power generation facilities after deregulation

- Favors cogeneration & polygeneration over new central power plants
- Cogeneration & polygeneration in China & India are essential, however, this is not in the best interest of regulated utilities
- However, cogeneration generally just reduces the rate of CO\textsubscript{2} growth

Ultimately must face up to CO\textsubscript{2} reduction & CO\textsubscript{2} sequestration

- Replace coal with NG, renewables & waste fuels where economical
- However, these options are limited & renewables appear over-sold

Conclusions

Must objectively consider fossil fuels with CO\textsubscript{2} sequestration

Retrofit of existing coal plants with CO\textsubscript{2} recovery appears competitive with replacement by NG, renewables or nuclear

- Key issues are future natural gas prices & the cost reductions if high pressure can CO\textsubscript{2} obtain a small byproduct value for EOR or CMB
- Gasification rebuilds can greatly increase the capacity, efficiency & environmental performance of existing coal power plants

Gasification based polygeneration plants are currently being built at commercial scale without subsidies

- Polygeneration has the unique advantage of also recovering CO\textsubscript{2} at potentially low incremental costs

Many opportunities for technical & economic improvements

- However, requires objective & transparent comparative analysis